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Using time-reversal to locate non-volcanic tremor and to fulfill the monitoring objectives of the nuclear-test ban treaty

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In this paper are presented the latest results of our group effort to apply Time Reversal (TR) to different seismology problems. The first problem considered is source location of non-volcanic tremor (NVT). NVT episodes involve quasi-continuous emissions of seismic energy making the identification of distinct events and phase arrival times very difficult. We locate 2 NVT episodes that were recorded near Hemet: one triggered by the 2002 Denali earthquake and one by the 2009 Mexicali earthquake. Locations indicate sources slightly off the known scarp of tectonic faults. In both cases, determination of the source mechanism is impossible. The second problem is determination of the depth of seismic events. There is currently no robust method to estimate the depth of small events (below Mw5.0), when depth determination is crucial in discriminating small earthquakes from man-made blast, since the blast will have to be within about 2 km of the surface where few earthquakes occur. We propose to use stacked autocorrelation (AC) signal to extract depth phases (i.e. phases reflected off the surface). AC is a variant form of TR. We show promising results from sparse IRIS stations in China for three nuclear blasts and a deep earthquake.

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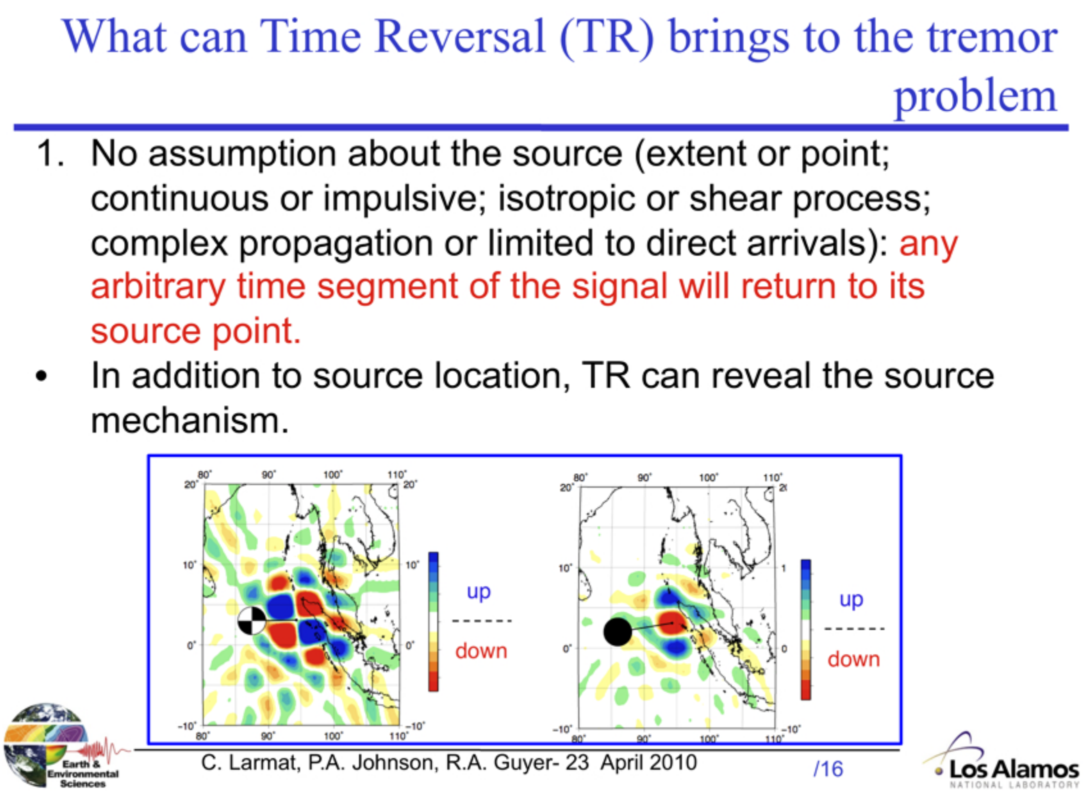
I. INTRODUCTION

This paper is based on some of the slides of a talk presented at the XV International Conference on Nonlinear Elasticity in Materials held in Otranto, Italy, from July 4 to 11, 2010. The presentation was made by Dr. Carène Larmat and was about research done in collaboration with Dr. Paul A. Johnson and Professor Robert A. Guyer and with the support of the U.S. Department of Energy through the LANL/LDRD Program.

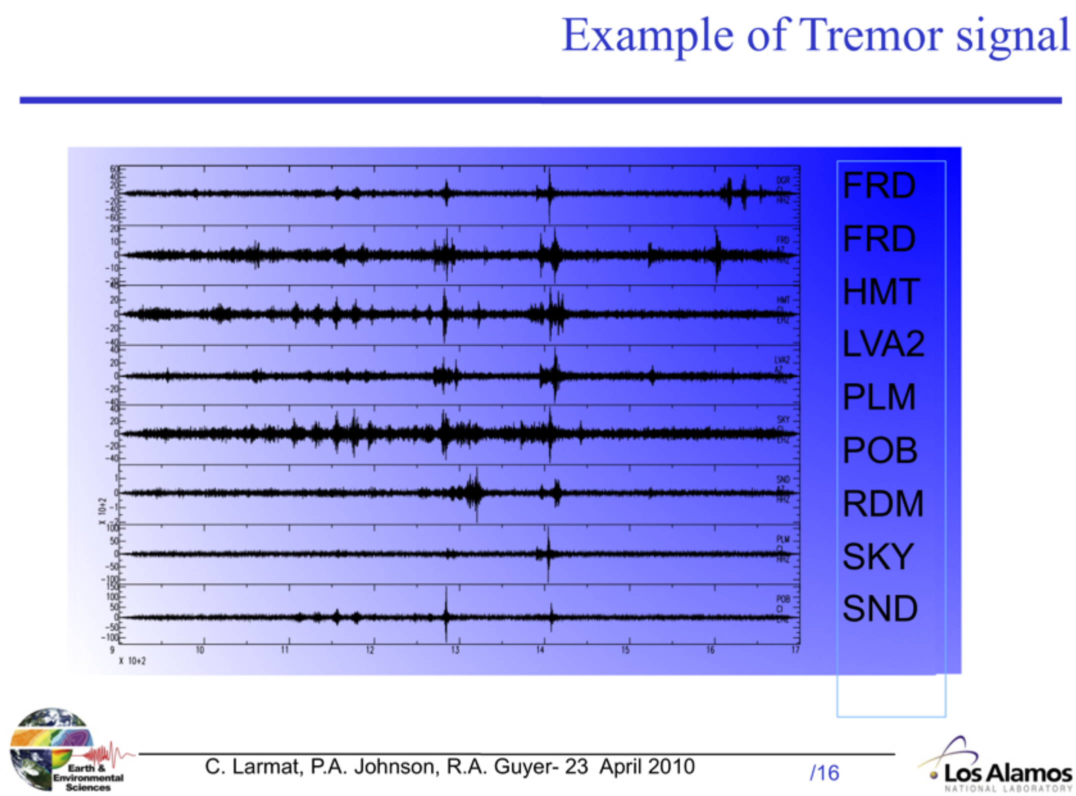
In the last decade, our group at Los Alamos has put a continuous effort to explore different application areas of Time Reversal (TR) with the unique approach of combining laboratory experiments with study of seismology problems. This has allowed us to explore the full spectrum of TR possibilities: *e.g.* location, characterization in terms of slip history, radiation pattern, multiple sources. The set of problems considered by our group includes acoustics applications (Anderson *et al.,* 2009a; 2009b; Ulrich *et al.,* 2009), Non-Destructive Evaluation (Ulrich *et al*., 2008; Johnson, 2009), seismology (Larmat *et al.*, 2008; 2009), and biomedical imaging (Muller *et al.*, 2009; Rivière *et al.*, 2010).
The motivation to use TR to current seismology problems is that TR thrives with complexity. First, TR has no problem with complexity such as 3D velocity models, presence of topography, finite size of the studied source, as long as the numerical scheme used to back-propagate the recorded signal correctly handles these propagation features. Second, TR uses the full waveform data including the scattered phases, contrary to state-of-the-art location techniques based on simple paradigms. The more scattering is present in the medium, the larger is the number of independent phases recorded on a given receiver (for example, the direct followed by a first reflected phase, followed by a second reflected phase…). All these different phases will converge and add up onto the source point when traveling backward and will improve the ratio of focus amplitude versus background noise as well as the location resolution (Dowling *et al.,* 1992; Fink *et al.,* 2000). Another interesting facet of TR is that any arbitrary recorded time-segment will automatically return to the source. Time-Reversal doesn't need any interpretation of the signals prior to the rebroadcast (Kennett, 1983). One application can be location of the origin of the various emergent signals that have been recently discovered thanks to the rapidly augmenting number of seismic networks worldwide.

Two important learned lessons from our work are presented on the first slide extracted from the presentation. This slide is entitled “What can Time Reversal brings to the tremor problem” but which could have been entitled with the generalizing “What can Time Reversal (TR) brings to seismology”. As already explained, TR allows to study the origin of any type of recorded seismic signal. A second point is that in addition to source location, TR allows the determination of the source mechanism (*i.e.* isotropic source versus dipole or quadrupole source). Knowing the source mechanism is key to try to link the seismic source to a generation process (*e.g.* shear slip, fluid motion).



In the following, we present our progress on the location of several NVT episodes using TR. We will also present some preliminary results concerning source depth determination using the Auto-Correlation Method (AC), which is strongly related to TR.

II. TREMOR LOCATION

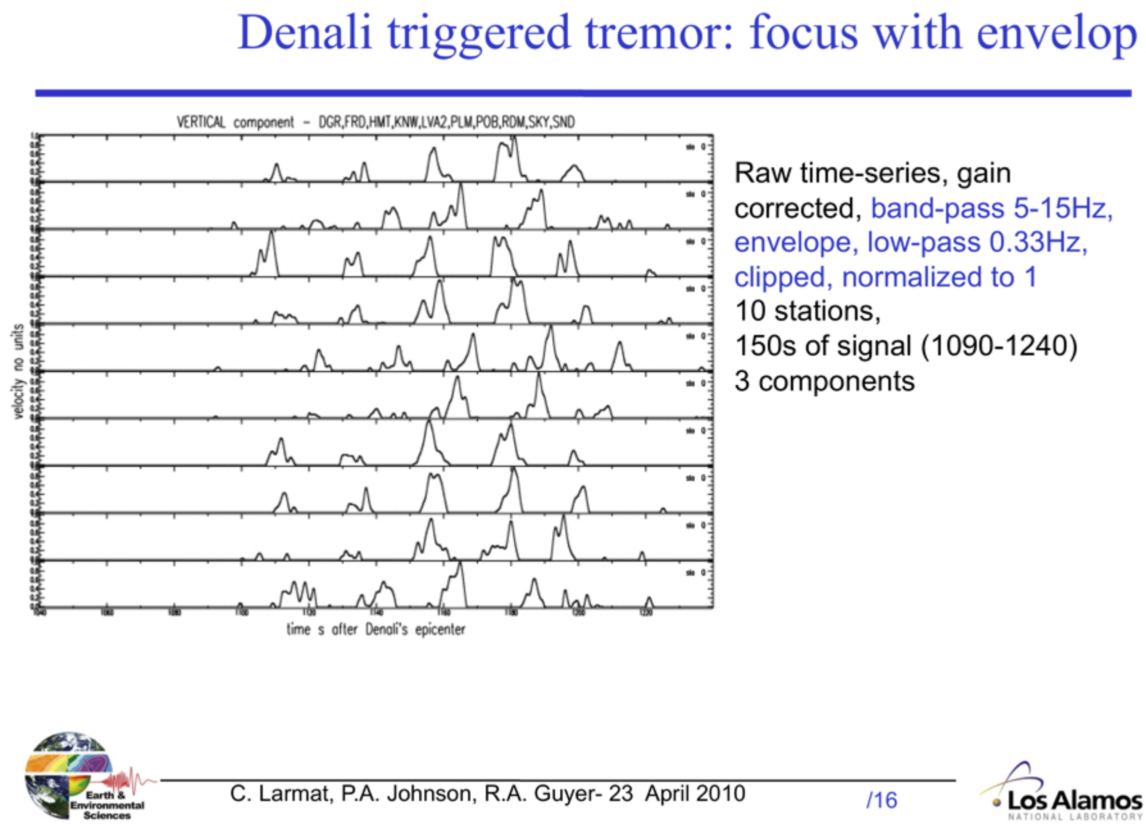


a. How TR can help with the NVT problem?

NVT (Non-Volcanic Tremor also thereafter simply referred as tremor) episodes involve quasi-continuous emissions of seismic energy making very difficult the identification of timing features such as phase arrival times often used to locate earthquakes (see slice "Example of Tremor Signal"). NVT is manifest as coherent increase of "noise" level between different stations. Obara (2002) demonstrated the indigeneous nature of NVT (*i.e.* source in the Earth in contrast to biosphere atmosphere related or man made events). Seismologists have developed a suite of novel methods to address to locate the challenging tremor. Obara (2002) measures the delay between a pair of station by computing the cross-correlation of the envelop of the signal. The location errors in this method are typically large due to the large pick errors when using the envelop. Kao&Shan (2004) have developed a "Source Scanning Algorihtm" (SSA) based on the back-projection of the waveform onto a tested source location. The source is identified as a point of maximum brightness. This method can be seen as a simplified form of Time-Eeversal for which the back-propagation is limited to a simple shift-in-time of the time-series. This method has been successful to provide convincing location methods for the NVT events in the North Cascadia Margin area but with a large spreading of the locations. La Rocca *et al.* (2010) use "array analysis" (*i.e.* measurement of apparent velocity and back-azimuth through an array of receivers) combined with P and S arrival measurement (obtained by cross-correlating the vertical and horizontal components of vertically incident energy) and found that the sources of NVT recorded in July 2004 in the

Cascadia area are confined to the subducting slab-mantle interface. Shelly *et al.* (2007) perform a systematic cross-correlation based search of NVT episode using LFEs waveforms to extract P-arrival time. The method has been successfully applied to locate NVT sources in Japan and triggered tremor near Parkfield (CA) (Shelly, 2010).
Despite more and more numerous convincing studies about the shear nature of the tremor sources (Ide *et al*., 2007), seismologists are still debating on the origin and source mechanism of this phenomenon. Much progress is still needed on the current resolution on tremor source location. Implications are enormous as tremor can be used as a proxy for slow slip in deep part of seismically active faults (Hiramatsu *et al.,* 2008).

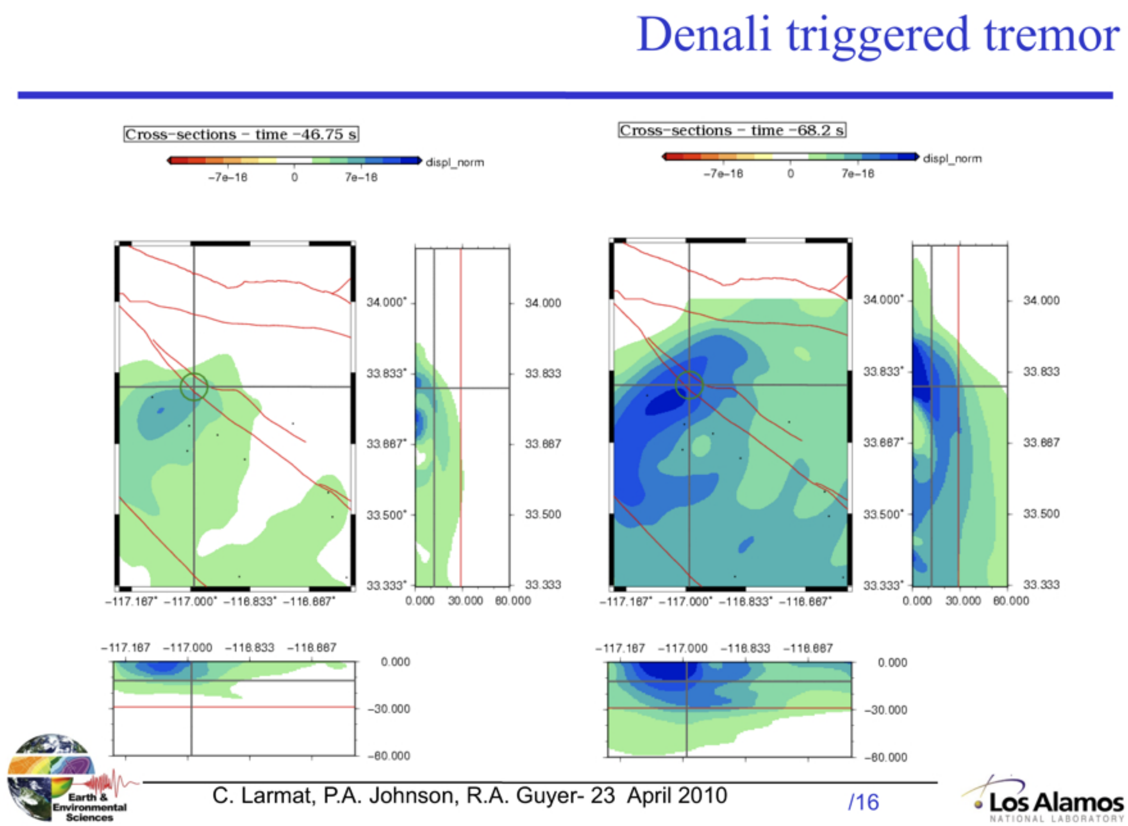
We propose to use Time-Reversal to locate the source of two triggered tremor episodes recorded near the city of Hemet along the San Jacinto fault which belongs to the San Andreas fault system. The first episode was triggered by the 2002 M7.9 “Denali” earthquake that was 3,600 km away. The second episode was triggered by the M6.9 so-called “Mexicali” earthquake. This earthquake occurred in the Gulf of California area on the 3rd of August 2009 (about 500km away from Hemet). We use the basin version of the spectral-element based package SPECFEM3D (Komatitsch *et al.*, 2002) to perform the back-propagation. The grid used to perform our inversion samples a volume of 88km (N-S) x 71 km (E-W) x 60 km (vertically) around the supposed source location (see maps below). The number of elements used is about 2.8 millions (*i.e.* about 2e8 grid points). This mesh can resolve frequencies up to 3.35Hz (average distance between point being of the order of 30m). The time sampling is of 1.1e-3s respecting the CFL condition. The back-propagation modeling is run on a middle-size cluster of LANL. A typical run involves 256 processes and takes 15h to time-reverse a time-series of 150s.
The velocity model used is a 3D smooth velocity model built by compiling borehole measurements and local tomography results for the California basin (university of Harvard).



b. Triggered tremor by the 2002 Denali earthquake

The signal of NVT triggered around the San Jacinto segment of the San Andreas fault is typically in the 1 to 10 Hz frequency range (Nadeau & Dolenc, 2005), when our numerical model can only handle frequencies up to 3.35Hz. The set of stations showing evidence of tremor amounts to 10 stations that are indicated as black points of the maps shown below. We chose to locate the tremor that appears coincidentally with the arrival of the surface wave at Hemet, approximately 18mn after the initiation time of the earthquake. We first try to locate the tremor source by time-reversing the waveform of this time-window after low-passing the waveforms up to 3.35Hz. The snapshots of the norm of the time-reversed displacement at different times show no evidence of focus. We then decided to time-reverse the envelop of the tremor signal. We first band-passed the time-series between 5 and 15 Hz, compute the envelop, low-pass this signal up to 0.33Hz and keep only the signal that is above the RMS of the time-series (the points that don't pass the threshold are put to zero). The signal was then normalized to 1 meaning that the maximum of the obtained time-series was put to 1. The signal obtained for the vertical component for each of the 10 stations is shown on the slice above. The signal is limited to burst of energy at the moments where the tremor signal was locally maximum.

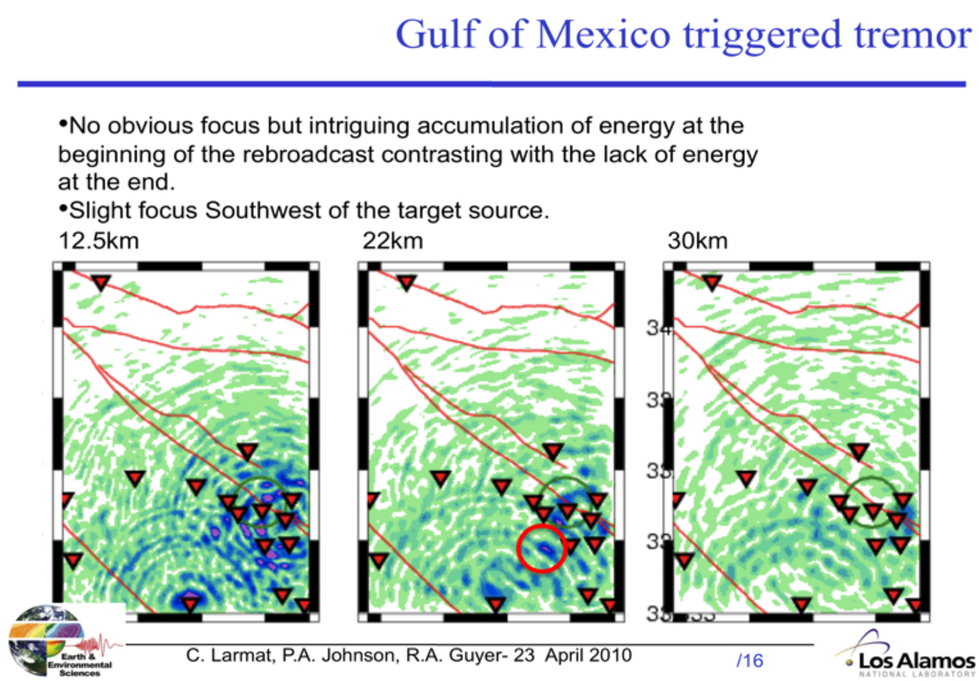
On the slide shown on the next page "Denali triggered tremor", are presented the snapshots of two moments where a focus distinctly appears. This point source is about 7km off the surface trace of the fault and is 12km deep. Beside the norm of the time-reversed wavefield, we look at several other imaging fields (divergence, horizontal strain) that should highlight separately different characteristics of the seismic source as explained in Larmat *et al.* (2009), in order to determine the nature of the seismic source (volumetric versus pure shear). Unfortunately, these imaging fields show no evidence of focus. The procedure imposed on the original waveforms (consisting of computing the envelop, severely low-pass the signal and clip all low amplitude signal) has reduced the time-reversal procedure to a simple location based on the maximum of interaction of the different energy burst send back. All amplitude or phase information that could have led to the correct construction of the original characteristic of the seismic source has been lost.



c. Triggered tremor by the 2009 “Mexicali” earthquake

Another NVT tremor episode was triggered in the same area on the 3rd August 2009 by the passage of seismic waves generated by the M6.9 earthquake that occurred in the Gulf of California, 500km away. The station coverage is better with 16 stations (indicated by the red closed triangles on the map below). We chose to time-reverse a time-window of 150s that displays some tremor evidence about 15mn after the initiation of the earthquake (so way after the passage of the surface waves). The waveforms recorded on the 16 stations and on the three components (except for 4 stations for which only the vertical component is available) was low passed up to 3.35Hz, interpolated to the correct time-step (imposed by the modeling), flipped in time, and sent back into the numerical model as point forces acting on the surface. Contrary to the tremor triggered by the Denali earthquake, a focus does appear with this simple treatment. It is located at 22km depth and about 5km off the surface trace of the fault (see slice “Gulf of Mexico triggered tremor”).

This focus is barely above the background noise level but there are several arguments to assert that this point is actually a source location. First, 3 successive periods can be clearly distinguished when watching the time-reverse movie: A first period when the signal is slowly building up but there is no manifest focus; A second period of 20s showing 5 successive hits on that particular point; Finally, a third period where the energy slowly escapes from the model. The second argument is that despite its small amplitude relatively to the background, this point stands out as a particular point when the energy gets localized. When comparing maps at different depths such as the ones presented on the slide, the focus appears clearly at 22km depth when the other maps display a more diffuse wave-field. The same observation can be done when comparing snapshots at the 5 focus moments and snapshots at other moments.
We then look at the different imaging fields and unfortunately these latter don't bring any insight into the nature of the source. Both maps based on the compression and shear-type motions show signs of focus, with the localizations being at different times and/or different locations than the norm of the time-reversed displacement.



d. Conclusions; Perspectives

In this paper, we present our progress on the difficult task to locate non-volcanic tremor (NVT) using TR. NVT episodes involve quasi-continuous emissions of seismic energy making the identification of phase arrival times and even the NVT episode itself very difficult. The station coverage is usually poor and tremor is a high-frequency signal (>5Hz) compared to the resolution of currently available velocity models. We locate 2 NVT episodes in South California: one triggered by the 2002 Denali earthquake and one by the 2009 Mexicali earthquake. For the first episode, the location was obtained by time-reversing a low-band passed version of the envelop of the signal. We manage to get a convincing focus for the second episode by sending the waveforms low-passed up to the frequency resolved by the numerical grid. This suggests that the second episode is more low frequency than the first one.

Locations indicate sources slightly off the known scarp of tectonic faults for both cases. Determination of the source mechanism (*i.e.* isotropic versus shear character) turns out to be impossible. This suggests that the time-reversal reconstruction is not accurate enough in order to constrain correctly the characteristics of the original source. The first problem is that the maximum of tremor activity is above the cut-off frequency of 3.35Hz. We are currently working on designing stable meshes to resolve higher frequencies. The second problem is the fact that our effort is hampered by inadequate knowledge of the velocity model to correctly predict seismic waveforms at these high frequencies. We can try to assess the inaccuracy of our location by testing other velocity models beside the currently used 3D model.

III. SOURCE DEPTH DETERMINATION USING AUTO-CORRELATION

a. The problem

The USGS estimates the number of earthquakes of magnitude 3 or more to be 130,000 per year. The National Earthquake Information Center (NEIC) now locates about 20,000 earthquakes each year or approximately 50 per day. As the number of stations increases, the number of small events detected increases, it becomes important to develop new discrimination method to screen small events recorded at regional and sparse networks in order to eliminate them from the pool of possible nuclear tests. This will ease the operational burden on the United States National Data Center (USNDC) and strengthen verification of the Comprehensive Test Ban Treaty.

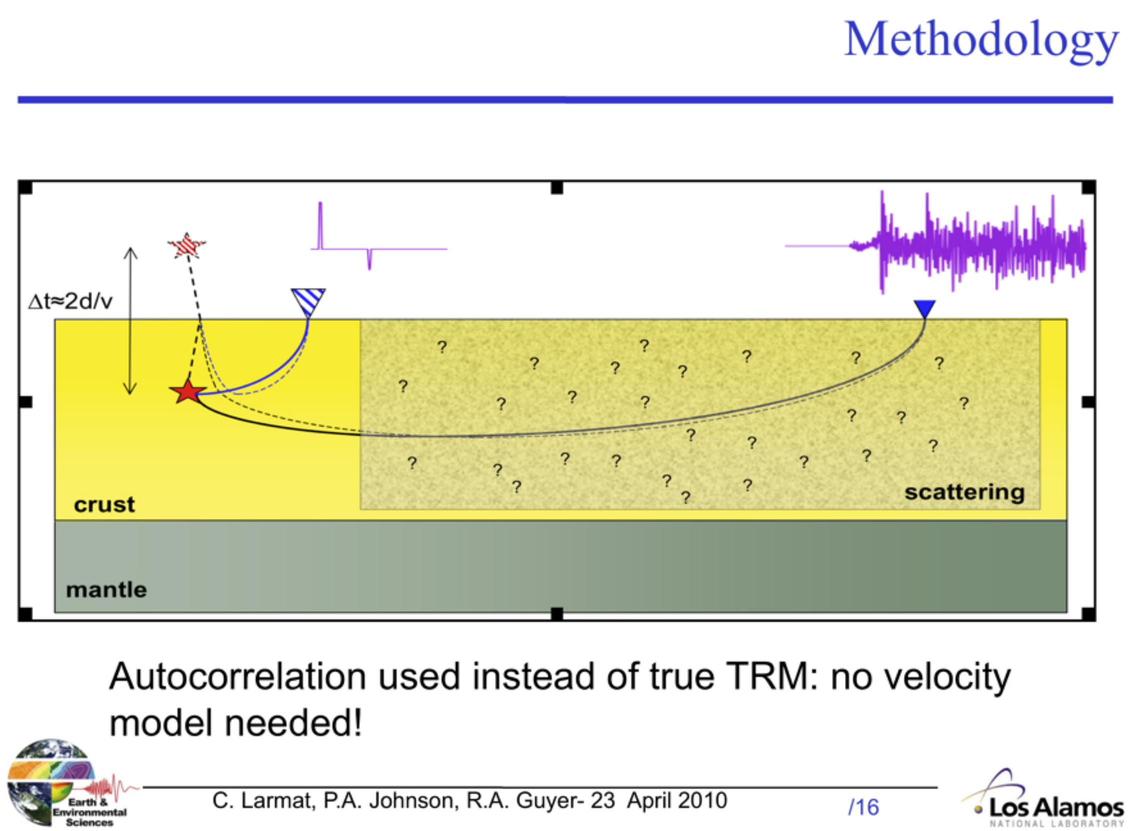
A method that could place with sufficient accuracy small events below a depth where a nuclear test could be emplaced would be a powerful discriminant. But currently we know of no robust event depth estimation for small shallow seismic events. Methods intended for small earthquakes recorded at regional distance must specifically address the problem of crustal scattering (Zhang *et al*., 2002). Crustal scattering acts in three ways: coda generation, attenuation, and incoherence of arrival time due to path effect (Toksöz *et al.,* 1991). In the following, we are testing simple scheme based on AutoCorrelation (AC) to extract the deterministic part of waves scattered in the crust.

b. The method

The idea of using correlation to extract phase information from short period seismic coda is not new. (Aki, 1957) and (Toksöz, 1964) have used microseismic data to determine the local velocity model. Claerbout (1968) used ambient noise to retrieve the 1D-layered structure. Recent important advances in the application of the approach to noise data is transforming local tomography studies (Campillo&Paul, 2003). But to the best of our knowledge, the potential of the application of AC to regional coda phases has not been thoroughly investigated.

The figure shown on the slide “Methodology” illustrates the coda generation process as scattering induced by lateral heterogeneities in the crust and upper mantle. The presence of lateral heterogeneities in the crust and upper mantle dilute any individual phase arrival into a long-lasting coda signal. The AC signal is close to the signal produced at the source point by the time-reversal procedure as the two signals involve the auto-correlation of the Green functions (Larose *et al.*, 2006). As a companion method of TR, AC acts in similar way. Contrary to most of the methods tested for depth determination, a strong scattering is not a limitation of AC: the stronger is the scattering, the closest to a delta-function will be the auto-correlation of the scattering part of the signal (in terms of TR, this means that all the scattered phases converge back to the source point). When this happens, the AC signal consists in the auto-correlation of the source time function convolved with the auto-correlation of the near-source propagation terms. This latter contains the reflection off the surface of the direct arrival, which can be used to determine the source depth. In summary, instead of looking at the complex signal recorded after scattering, the AC provides a signal that is the auto-correlation of the signal that would be recorded at a close station (as presented on the figure). The effect of attenuation and fluctuation of the velocity structure at regional distance are minimized. Dispersion (i.e. distortion of the original pulse as the signal propagates) is also not a problem as the time-reversal process brings all the phases back together to build the original pulse.

Finally, notice that TR and autocorrelation are different in practice, as the velocity structure does not need to be documented when computing the auto-correlation.



c. Results from sparse networks in China

We present a study conducted with data of several earthquakes and some nuclear blasts in Western China, as a proof of concept of the efficiency of the AC method with sparse networks. The data were BHZ channels of velocity records furnished by IRIS and mostly coming from the networks IRIS/IDA, IRIS/USGS, Kirghiz Telemetered Network, and Kazakhstan Network. We use a MATLAB code developed by Pearce (2009) with slight modifications: First, we select the time-window corresponding to the Pg coda, remove the mean and trend before high-pass filter the signal to remove the microseismic noise. The signal is then transformed into its Hilbert transform before the Time-Frequency Correlation (TFC) function is computed for each traces (see equation 1). The value of the TFC is the value of the correlation of the signal with its version shifted both in time (time delay Δt) and in frequency (frequency shift Δf).

$$TFC_R(\Delta f, \Delta t) = \sum_{j=1}^{J} E_R^*(t_j) E_R(t_j - \Delta t) e^{2i\pi \Delta f t_j} \qquad \text{Eq. 1}$$

The absolute value of the TFC is then stacked over the number of stations for each (Δt,Δf). The curves versus the single variable Δt presented on the figure of the slide "Results" are obtained by summing the different contributions of Δf. The M5.0 Kazakhstan event was a deep event with a well-constrained depth estimate of 29.7 km by the USGS on their monthly Earthquake data report. We found a time-delay of 10s, which correspond to a depth of 29km assuming a velocity of 5.8km/s for the P wave. The peak at 10s is a robust feature of the analysis and persists as we vary the processing parameters: changing the corner frequency of the high-pass filter, working with displacement records instead of velocity; and applying a correction term that we design to take into account the different effective lengths of the time-window at each stations (related to the number of samplings on with the Fourier transforms are performed). The shape of the AC function obtained for the nuclear blast is very different with several peaks and most of the energy for time-delays below 5s.

An intriguing question raised by this example is the interpretation of the smaller peaks located very near the central peak. Their apparent close association with the central peak suggests that they are a signature of the STF rather than near-source features. In this case, the two pairs of peaks displayed by the nuclear blast might be related to spalling/freefligth and slap down processes during the explosion.
An interesting following-up of this study would be to explore this kind of questions by conducting a synthetic study of the effect of source parameter on the AC method.

IV. ACKNOWLEDGEMENTS

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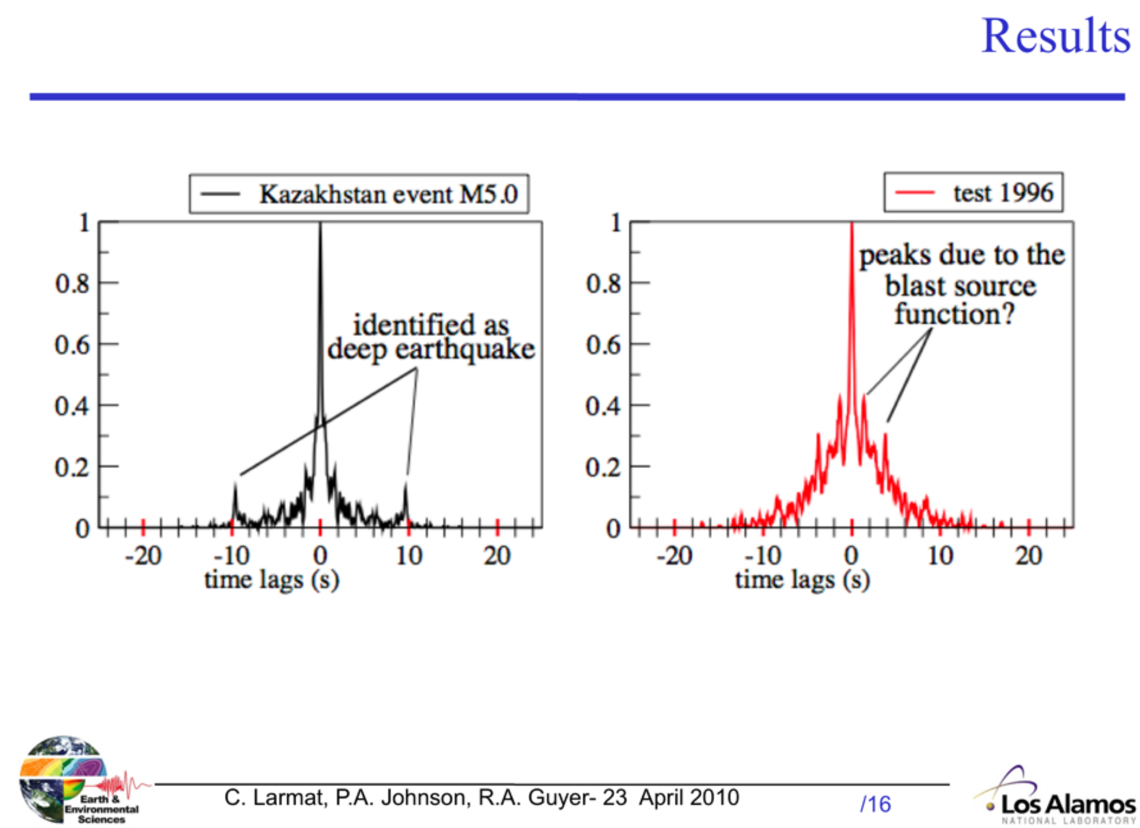

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